Towards Early Warning Signals for Desertification

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Abstract
Dryland ecosystems cover a large share of the world's terrestrial surface. Deficiency and spatio-temporal variability of precipitation as well as low vegetation growth rates make dry rangelands prone to degradation, especially under changing climate and intensified land use. Degradation often occurs gradually but sometimes, a sudden and surprising shift from a healthy to a degraded rangeland can be observed, where perennial grasses are lost, and bare soil is exposed. If such changes are sudden and irreversible, they are coined a tipping point. Due to their abrupt appearance, it is a great challenge to discover early warning signals that precede the regime shifts. Theory predicts that variance and autocorrelation in state conditions could be used as early warning signals. However, these theoretical assumptions have rarely been tested in real ecosystems. Here, we use a data-based approach to contribute to filling this research gap using desertification processes in a semi-arid rangeland as a case study. In order to test the applicability of theoretical early warning signals for tipping points, we looked at a dataset from Widou, Senegal, that includes annual observations of rainfall, grazing intensity and primary production from 1981 – 2007. We analysed productivity-based metrics, such as rain use efficiency, in order to detect patterns that may precede a shift between alternate stable states. Strong signals of a regime shift were detected that were expressed in a sudden alteration of species composition and general decline of productivity after a drought. However, we did not find any changes in the theoretically proposed parameters that may reflect early warning signals for a critical transition, i.e. the regime shift was essentially unpredictable. We suggest that while the theory around tipping points and early recognition thereof may be robust, the applicability of theoretical concepts to the real world may be challenging.
Key words: Desertification; tipping point; early warning signal

Introduction
Under currently changing climatic conditions and intensified land use, dry grasslands are prone to degradation because of the deficiency of precipitation and spatio-temporal variability thereof. The transition from a healthy to degraded state has been observed as a sudden and surprising shift, where feed grasses are lost and bare soil conditions dominate. This transition is often discussed in the context of regime shifts, or tipping points, where a system shifts from one alternative stable state to another (Rietkerk et al. 2004). These transitions are often considered irreversible without major renaturation efforts (Angeles et al. 2013). Being able to forecast these transitions before they actually occur is thus of utmost importance and a crucial prerequisite for the implementation of targeted management strategies. Whether or not a regime shift is near, might be detected with generic indicators that together are known as the phenomenon of critical slowing down (CSD) (van Nes and Scheffer, 2007). CSD works across a variety of complex systems and comprises the patterns that form when return rates to equilibrium slow down (Carpenter and Brock, 2006). Slowed down recovery is expressed in a greater variance as well as increased temporal correlation before a regime shift and these patterns are proposed to arise before many different transitions in ecosystems, including desertification (Scheffer et al. 2009). Bestelmeyer et al. 2013, tested whether measurements based on patchiness and vegetation cover might serve as early warning indicators and found that grass cover was the main determinant of variation in recovery, therewith signalling an upcoming transition. This gives support to the idea, that simple productivity–based metrics might already contain sufficient information to analyse whether patterns related to early recognition of critical transitions arise in the context of dryland degradation. Productivity-based metrics are known to retrospectively capture structural changes in vegetation related to desertification (Verón and Paruelo, 2010). Rain use efficiency (RUE) represents one of these metrics. It relates net primary production to rainfall and therefore informs about the system's ability to use rainfall. Hence, it may indicate degradation of the system (Kaptué et al. 2015).
In this study we investigate the influence of drought and grazing pressure on threshold dynamics in drylands and the potential of simple productivity-based metrics as early warning indicators. We hypothesize that annual RUE is sensitive to changes around tipping points and shows patterns of increased variance and temporal correlation, with more pronounced patterns for more heavily grazed systems.

Methods and Study Site

We analyse a long-term set of field-derived productivity data that was collected and first published by Miehe et al. in 2010. The ecosystem is characterized as a thorn bush-savanna with the herbaceous layer mainly comprised of annual grasses and is primarily used as rangeland. Aboveground biomass of the herbaceous layer was harvested annually at the time of maximum vegetation development at the end of the growing season to measure annual net primary productivity (ANPP). Peak standing crop was measured in four different grazing intensity regimes i.e., "no grazing/exclosure", "low grazing", "high grazing" and "free grazing". Intensities were created by excluding animals for the exclosure treatment, or by controlling livestock numbers for the low and high grazing. The free grazing treatment was considered the highest grazing intensity; in this case livestock was managed by the local community. As a measure for drought, we used the effective rainfall of the hydrological year (calculated by Miehe et al., 2010). Miehe et al. report that degradation events following the drought became visibly apparent in the grazed study sites in 1996. After this year, biomass production declined severely in the grazed plots.

In order to find symptoms of critical slowing down (CSD) we assessed patterns before and after this potential regime shift in 1996. We compared these two phases in our time series for a better understanding of the dynamics in CSD-related metrics around the potential shift. The variance over time as well as temporal relationships within the time series were analysed in order to display symptoms of slowed down recovery. Rain use efficiency (RUE) was calculated by dividing ANPP by annual effective rainfall . Patterns in the variance of RUE were identified by computing the variance around mean RUE within sliding windows of 4 years.We used forecasting to explore changes in the pattern of temporal relationships before the degradation event. Therefore, we based our analysis on a simple naïve forecasting model, which takes into account the start and the end of the time series and the values from previous years. Predicted values can then be compared to the observed values and deviations can be detected (Equation 1). Deviations are reflected in the forecast error of RUE over time (ε_t) , which was calculated using a random walk with drift model (Equation 2), which predicts every value from the last observation ($\hat{y}_{t-1}$) and the average change across all observations ($\frac{y_T - y_1}{T-1}$), where T is the total length of the time-series, allowing the forecasts to have an upward or downward trend, which would be desirable in this case (Hyndman and Athanasopoulos, 2014).

$$\varepsilon_t = y_t - \hat{y}_t \qquad (1)$$

$$\hat{y}_t = \hat{y}_{t-1} + \frac{y_T - y_1}{T-1} \qquad (2)$$

Since we were interested in inaccuracy of forecasts, independent of the direction of inaccuracy, we used absolute values in the following analyses. In order to test whether the forecast errors or the variance differs between grazing intensity and the phase in our time-series (before and after the degradation), and whether there is a combined effect of these factors, we used a Linear Mixed Model (LMM) with forecast error / variance in RUE as response variable, grazing intensity and phase as fixed factors and site as a random factor. Specific effects of phase within grazing intensity was tested by using post hoc pre-planned contrasts in combination with a Dunn-Sidak correction. Data were tested for normal distribution by a visual assessment of the histograms of the collected data (Zuur et al.2010). In order to fulfill assumptions of LMMs, the data were log-transformed. For testing homogeneity of variances, the Levene-Test was used, and results fulfilled the assumption of homoscedasticity. Plots were created using the loess-smoothing method that is based on a local regression approach which fits multiple regression to small subsets of the data.

Results

The absolute forecast throughout the study period showed no explicit increase before the expected regime shift. However, forecast errors are overall higher in the time before the supposed regime shift than after it for the grazed treatments, but not the ungrazed sites (Fig. 1). There was an overall decrease in the forecast error after degradation in phase 2 and effects were significant for the low and high grazed sites ($t= 3.35$; $p= 0.0034$ and $t= 3.074$; $p<0.0088$ respectively). Sites subjected to the free grazing treatment likewise had a strong trend to increase in predictability after the reported degradation, however this was not detectable through statistical analysis ($t=1.060$; $p= 0.7450$). Ungrazed sites showed constant forecast errors, across both phases ($t=-0.239$; $p=0.9987$) (Fig. 2).

Variance was generally higher before the supposed regime shift, and decreased thereafter. However, the increase might not be read as a classical increase in the context of CSD, because we can see a slight declining pattern before 1986. The decline in variance after 1995 is stronger and faster for grazed sites than exclosure sites (Fig. 3).

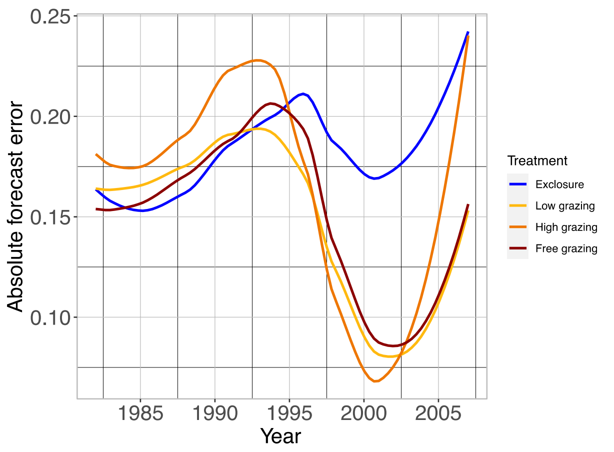

Figure 1: Loess-smoothed absolute forecast errors over time for 4 different grazing intensities. There is a strong forecast accuracy for grazed plots after 1995.

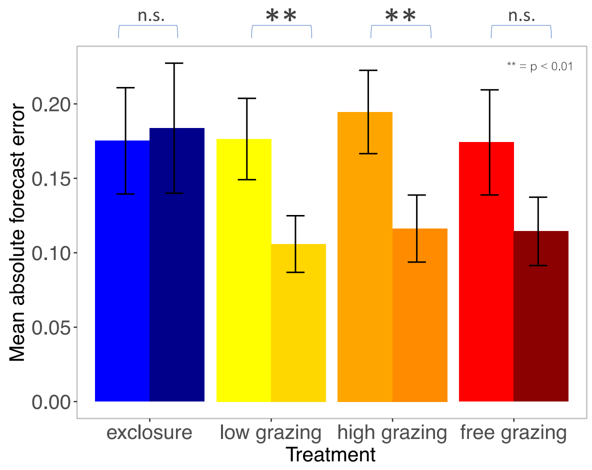

Figure 2: Result of the LLM and pre-planned contrast analysis for differences in forecast errors between phase (left bars are pre-1966 and right bars are post-1966),within grazing. Figure shows the mean absolute forecast error per treatment with doubled standard error for the mean. Significant differences are highlighted

Testing the mean variance in RUE against effects of grazing intensity and phase (before or after the reported degradation), showed that grazing affects the mean variance in RUE for all grazed sites (t=7.334; p<0.001 for low grazing, t=7.337; p<0.001 for high grazing, t=6.409; p<0.001 for free grazing), with no change in the variance in the ungrazed sites (t= 0.302; p=0.9968) (Fig. 4).

In general, there is a strong influence of grazing on CSD-related variables, in particular in combination with the phase. No grazing constantly leads to equal values of these variables across the two phases of the time series, whereas the values in the low and high grazing treatment differ significantly between phases, resulting in higher variance and less predictability before the reported degradation and expected critical transition. The free grazing treatment has likewise a strong trend to display this pattern.

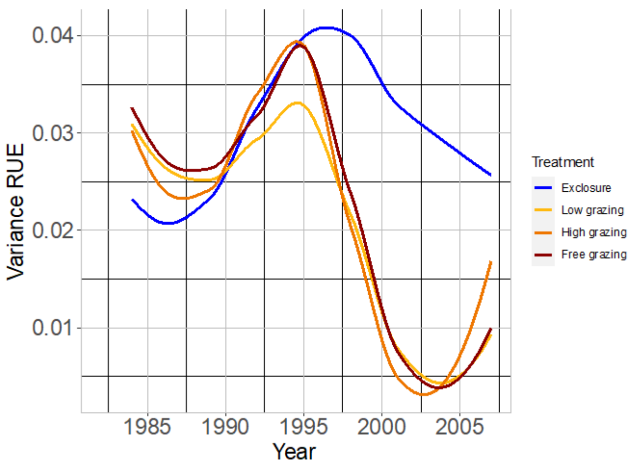

Figure 3: Loess-smoothed variance in RUE over time for 4 different grazing intensities. There is a strong decrease in variance after 1995, which is drastic in grazed sites. Dynamics of variance in RUE over time in ungrazed sites are less extreme.

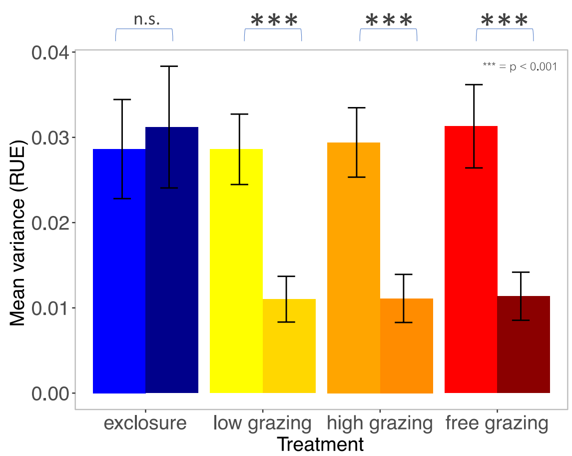

Figure 4: Result of the LLM and pre-planned contrast analysis for differences in variances between phase (left bars are pre-1966 and right bars are post-1966),within grazing. Figure shows the variance in RUE per treatment with doubled standard error for

Discussion [Conclusions/Implications]

Our results suggest that the ecosystem we studied is subject to threshold responses and that the strength of disturbances inducing such, might be milder than we thought. Signs for a supposed state shift were equally present irrespective of grazing intensity, which has serious consequences for concepts in rangeland

management. We found a clear discrepancy between predictability of RUE between grazed and ungrazed sites, with better predictability in the grazed sites after degradation.
This might imply that a critical transition occurred, where the system went into an alternative stable state after 1995, resulting in more accurate forecasting ability. Investigating critical slowing down via increased variance yielded similar results. Results show an increase in variance before 1995, followed by a strong decrease in the variance in RUE after the reported degradation, reflecting a higher likelihood for a transition into a new stable state.
Whether or not the apparent fluctuations in variance and predictability around a degradation event fit into the context of CSD is, however, unclear. The extent of the time series used to predict regime shifts is critical, because natural fluctuations need to be separated from the threshold response. In a system where the typical generation time of the response organisms is more than one year, even several decades might not be enough. Like in other studies about regime shifts (climatic, econic, etc.), it might be necessary to observe > 100 time steps in order to make sound conclusions (Andersen et al. 2009).
Although we detected rangeland degradation using the available metrics, our analyses showed that there was no clear pattern indicating a critical transition before it happened. Against the expectations that grazing intensity would have an impact on the systems' likelihood to desertify, there was no difference between low, high and free grazing in the dynamics during/ before degradation, noting that herding control was abandoned in dry seasons after 1992. The data suggests that a combination of disturbances, i.e. repeated drought events as well as grazing by livestock, can drive drylands towards a tipping point. However, detecting the proximity to transition remains beyond recognition. One way to overcome the problem timeseries of insufficient extent may be the application of remote sensing (Nijp et al.2018). These methods may open up the possibility to monitor drylands over large areas and time periods, which may enable us to predict non-linear responses to environmental change in the future.

Acknowledgements
We thank Sabine Miehe for the access to the data we used to perform this study.

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